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Structure of 3D Printed Ti-6Al-4V Alloy after Low-frequency Processing

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Abstract. The structure and residual elastic stresses in 3D printed (Selective laser melting) Ti-6Al-4V samples after the low-frequency vibration processing were investigated. The studied samples were manufactured horizontally in respect to the building platform. Different vibration oscillations modes (vertical, horizontal, and elliptical) were chosen for study. The oscillations were done with frequency of 16 Hz, and a processing time was 20 minutes. Studies shown that 3D printed samples had a high level of residual elastic stresses, which were changed after vibration treatment. The influence of the low-frequency processing on the phase composition of the alloy was found.

1. Introduction

Analysis of the residual stresses is one of the important tasks solved in the design of metallic parts and constructions. Residual stresses can have both the negative and positive effects on the structure of the materials. In many cases, the decrease in the level of residual stresses in the critical parts of the metal constructions leads to the increase of their reliability and durability. Most impact of the residual internal stresses is found to be associated with the limitation of exploitation capacity of the material under cyclic loads, small plasticity of the material, or at low temperatures [1]. Residual stresses are present in the material, regardless of the presence or absence of external influences. They arise because of local plastic deformations from non-uniform heating, local external mechanical action, local structural-phase changes.

Vibration treatment has been successfully used for several years in the oil and gas industry for decreasing of the residual internal stresses in the welded joints [2]. This process is provided with the fact, that in the case of resonant vibration, high dynamic stress amplitudes appear in the structure of the metal, which significantly affect the redistribution of stresses in the entire volume of the material. It was found that the vibration processing of titanium alloys allowed one to reduce the residual internal stresses up to 60%. As it was also shown, the necessary frequency for such vibration processing of metals should be not less than 50 Hz [3].



High level of the residual elastic internal stresses was found in the Ti-6Al-4V alloys manufactured by selective laser melting [4]. Tensile twins given an evidence of the existence of the high level of the tensile stresses in the 3D printed Ti-6Al-4V material were observed in [5].

The aim of this work is to study the possibility of using the vibration treatment with decreased frequency to change the level of residual stresses in the Ti-6Al-4V alloy manufactured by the 3D printing.

2. Experimental

Ti-6Al-4V samples were manufactured by 3D printing using the selective laser melting (SLM) with the EOSINT M280 (EOS GmbH) 3D printing machine equipped with an Ytterbium fiber laser, and operating at 1075 nm wavelength (IPG Photonics Corp.). Standard regime recommended by EOS Company for manufacturing of the titanium alloys was used. The chemical composition of a powder corresponded to the ASTM B348 standard for medical titanium alloy (grade 23).

Structural studies were done with the transmission electron microscopes JEM 200CX and Tecnai G2 30 Twin with scanning systems and energy dispersive spectrometer EDAX, GATAN-filter image. Mechanical properties were measured at room temperature with nanoindenter NanoTest; the load $F = 32$ mN, load time was 10 s, and the measurement error was 2 %.

Vibration tests were done with the laboratory-training stand for assessing the impact of vibration on railway products. The vibration frequency was 16 Hz. Three consecutive oscillation modes (vertical, horizontal, and elliptical) were applied; a processing time was 20 minutes. The test modes were set with a personal computer used the licensed software.

An X-ray diffractometer DRON-3 with Cu $K\alpha$ radiation was used in this study. A sample cut from a bar of industrial medical hot-rolled and hot-pressed medical Ti-6Al-4V (ELI) alloy (ASTM F136, Grade 5) was taken as a reference [6]. Residual internal stresses leading to a shift in the X-ray lines were calculated from the formula [7]: $\sigma_1 + \sigma_2 = -\frac{E}{\nu} \cdot \frac{\Delta d}{d}$, where E is Young's modulus, ν is Poisson's ratio ($\nu = 0.3$ for Ti-6Al-4V), d is interplanar distance. Residual surface stresses were calculated from the following formula [8]: $H_{IT} - H_{IT,0}$, where $H_{IT,0}$ is the hardness of the reference sample, obtained with nanoindenter.

3. Results and discussion

TEM results are presented in Figures 1-4. Figure 1 presents the structure of the reference sample. Two-phase structure with plates of the HCP α -phase and grains of retained BCC β -phase can be observed in this sample (Figure 1a). SAED pattern taken from this region contains the reflexes of HCP and BCC phase in positions corresponding to the relationships between BCC and HCP crystal lattices (Figure 1b).

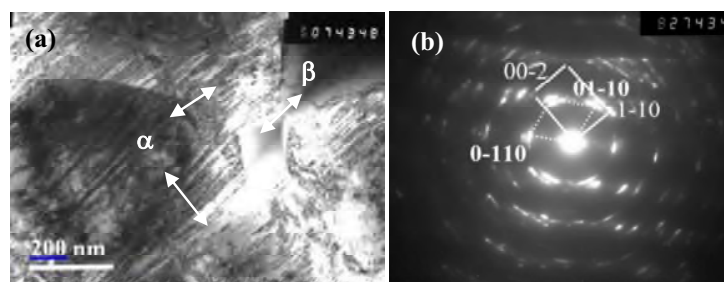


Figure 1. Microstructure of the reference sample: (a) the bright-field image; (b) SAED pattern to (a), zone axis $[0001]_{\text{HCP}} \parallel [110]_{\text{BCC}}$.

High cooling rates at SLM method result in the formation of the acicular α' martensitic phase in Ti-6Al-4V (Figure 2). Thin twins are also observed in the structure of the as-build sample (Figure 2b). The twin plane corresponds to the tensile HCP $\{10\bar{1}2\}$ twin plane (Figure 2c).

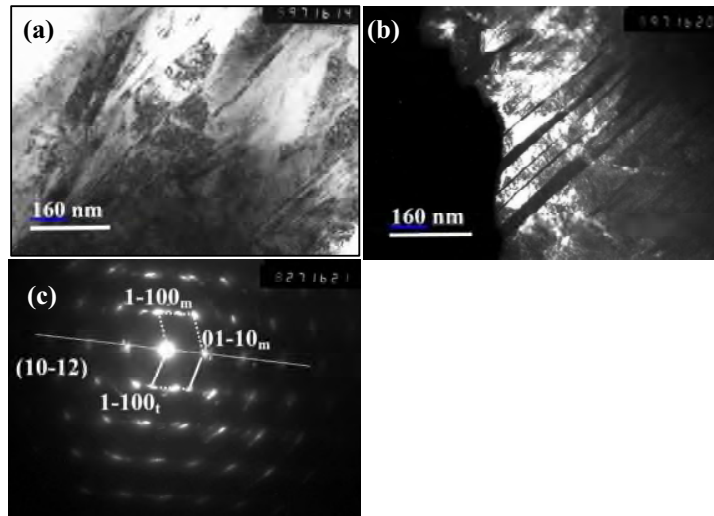


Figure 2. Microstructure of the as-build sample: (a) the bright-field image; (b) the dark-field image taken in HCP twin reflex; (c) SAED pattern to (b), zone axis $[0001]_{\text{HCP}}$, (10-12) twin plane.

The twinned structure with the same twin plane is also observed in the sample after vibration (Figure 3). High density of the defects one can see inside the HCP plates (Figure 3c). We did not found the recrystallization grains in the sample after vibration, which could testify the occurring the relaxation process in the structure. However the β -phase regions with high defect density were found in this sample (Figure 4).

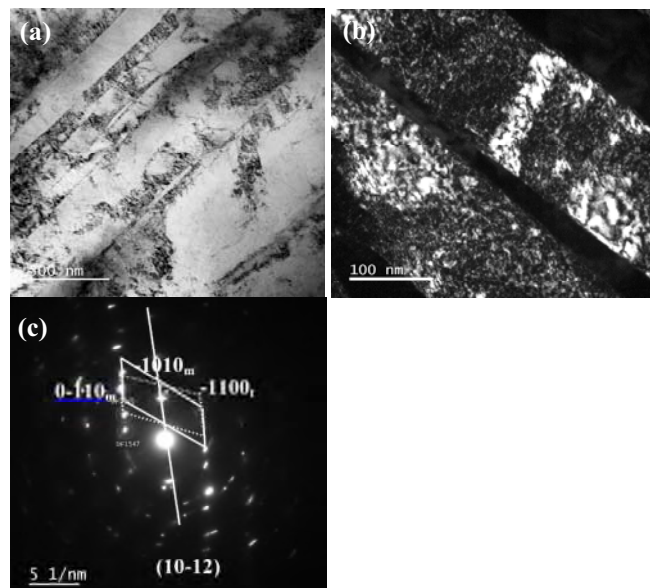


Figure 3. Microstructure of the sample after vibration: (a) the bright-field image; (b) the dark-field image taken in HCP matrix reflex; (c) SAED pattern to (b), zone axis $[0001]_{\text{HCP}}$, (10-12) twin plane.

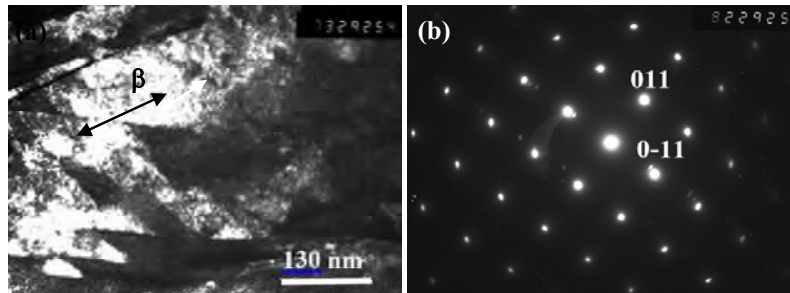


Figure 4. BCC region in the sample after vibration: (a) the dark field image taken in $(0-11)_{\text{BCC}}$ reflex; (b) SAED pattern to (a), zone axis $[100]_{\text{BCC}}$

According to X-ray analysis BCC phase is present in both samples the as-build and after vibration (Figure 5). However, in as-build sample almost all BCC diffraction lines coincide with HCP diffraction lines (Figure 5a). In TEM pictures, we did not find the BCC regions in the as-build sample. Probably, it is associated with the small and local presence of BCC phase in the structure of the as-build sample. After vibration the intensity of the BCC diffraction lines are higher than that in the as-build sample (Figure 5b). Last fact means that the vibration promotes the phase transformation $\alpha' \rightarrow \beta$.

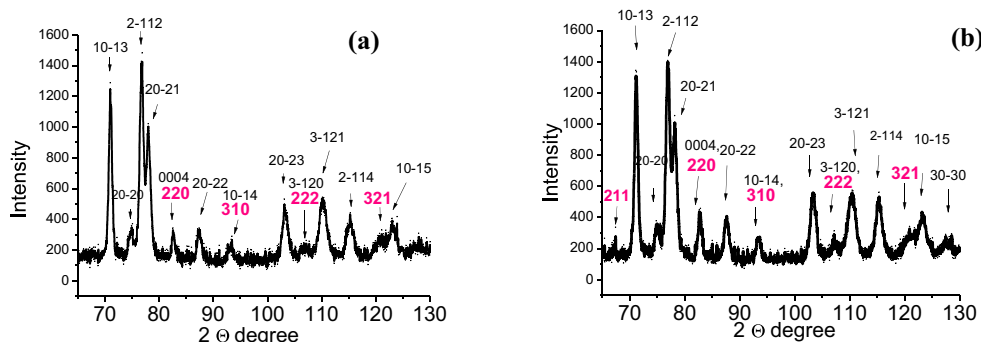


Figure 5. X-ray results of the studied samples: (a) as-build; (b) after vibration.

Results of nanoindentation and X-ray analysis are presented in Table 1.

Table 1. Results of nanoindentation.

Sample	E_{IT} , GPa	H_{IT} , GPa	Residual internal stresses (MPa)	Residual surface stresses (MPa)
reference	132	5.3	-	-
As-build	174	5.6	189	300
after vibration	177	5.9	458	600

As can be seen from the Table 1, the high level of the tensile internal stresses is found in the as-build sample. The results of X-ray and nanoindentation are correlates with each other. After vibration, the level of the residual elastic stresses is increased in comparison with that in as-build sample. In contrast to surface hardening treatments, vibration acts in the same way on both the internal and surface residual stresses.

4. Conclusion

Thus, low-frequency vibration used in this study affects the structure, phase composition and residual elastic stresses of the 3D printed sample. These results are promising for a possibility of using low-frequency vibration processing for titanium products manufactured by 3D printing. It is known that surface of the titanium products needs to be cleaned after every heat treatment. Low frequency vibration treatment is a non-expensive method, which allows one to save the material. It is shown that value of vibration exposure depends on not only the frequency, but also the amplitude and shape of the oscillations. Thus, by changing the modes of oscillation and the time of action, it is possible to select the optimal parameters for the relaxation process, which would promote the decreasing of the residual elastic stresses.

Acknowledgments

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